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MEMORANDUM REPORT ARBRL-MR-02969

ON THE UTILITY OF PLANE STRAIN APPROXIMATIONS FOR OBLIQUE IMPACT COMPUTATIONS

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October 1979

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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SECURITY CLASSIFICATION OF THIS PAGE (When Date Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER MEMORANDUM REPORT ARBRL-MR-02969	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ON THE UTILITY OF PLANE STRAIN APPROXIMATIONS FOR OBLIQUE IMPACT COMPUTATIONS		5. TYPE OF REPORT & PERIOD COVERED Final 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) J. A. Zukas G. H. Jonas J. J. Misey		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army Ballistic Research Laboratory ATTN: DRDAR-BLT Aberdeen Proving Ground, MD 21005		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 1L162618AH80
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Armament Research & Development Command US Army Ballistic Research Laboratory (DRDAR-BL) Aberdeen Proving Ground, MD 21005		12. REPORT DATE OCTOBER 1979 13. NUMBER OF PAGES 44
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Hydrodynamic Eulerian Code
Oblique KE Penetration
PHERMEX
HELP
Plane Strain Approximation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A study was made to determine the feasibility of using the plane strain mode of a 2D code in lieu of a 3D code for this oblique kinetic energy penetration problem. First, a comparison in a normal impact problem was made between the axisymmetric and the plane strain modes of the two dimensional HELP code. A volumetric relationship was given for the kinetic energy and the axial momentum of the projectile, but data scaling for other variables of the projectile and those of the target were not determined. Next, HELP in the plane strain mode was utilized to solve a long rod impact at 60° obliquity and the results were

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20. Abstract (cont'd)

compared with experimental data obtained at Los Alamos Scientific Laboratory. Finally, the oblique impact problem was also modeled with a three dimensional version of the EPIC code. A comparison of rod loss penetration depth, and penetrator and target profiles revealed very good agreement at early times when the penetrator density was greater than that of the target.

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I. INTRODUCTION

Long rod kinetic energy penetrators pose an important threat to armor. The analysis of the impact of a kinetic energy projectile, typically a cylindrical rod with large length-to-diameter ratio made of a high-density material, should account for the three-dimensional aspects of the impact and the failure of materials involved in the velocity range of interest. For reasons discussed elsewhere[1], very little analysis of oblique impacts has been done. Most of the effort in this area has been confined to experimental studies. Experiments, however, are complex, expensive, difficult to control and yield only minimal information. Time resolved data for ballistic experiments was generally unavailable. The need to understand the phenomenology and details involved in an oblique impact has led to the use of plane strain (two-dimensional) computations in the hope of deriving information useful to kinetic energy penetrator and armor designers. The use of codes in general has provided greater detail than can be obtained from experiments, but this approach leads to another series of complications (Table I).

In this report, we will discuss briefly the nature of the plane strain approximation and illustrate its successes and limitations with two applications. While some useful information can be extracted from plane strain simulation of oblique impact phenomena, much work needs to be done before such calculations can be used to support design efforts.

II. PLANE STRAIN APPROXIMATIONS

Computations at normal incidence can be performed routinely and economically and can yield excellent results for deformation fields when compared with experiments. Figure 1, for example, shows a comparison between a HELP[2] code computation of a staballoy rod striking 5.08 cm RHA plate at 1.0 km/s with results obtained at the PHERMEX facility of Los Alamos Scientific Laboratory[3]. The agreement is generally excellent.

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[1] *Jonas, G. H. and Zukas, J. A., "Mechanics of Penetration: Analysis and Experiment," Int. J. Eng. Sci., V16, pp. 879-903, 1978.*

[2] *Hageman, L. J., Wilkins, D. E., Sedgwick, R. T., and Waddell, J., "HELP, a Multi-Material Eulerian Program for Compressible Fluid and Elastic-Plastic Flows in Two Space Dimensions and Time, Revised Edition," Systems, Science and Software, SSS-R-75-2654, Topical Report, July 1975.*

[3] *Private Communication from E. Fugleso, J. W. Taylor and L. W. Hantel of Los Alamos Scientific Laboratory.*

The bulge at the target impact face in the computational results consists mostly of failed material - computational cells which have suffered a density reduction of 40% or more. This would normally be seen in a radiograph as a cloud of debris particles. However, the masking used in the experimental setup precludes recording of either front or rear bulging of the target plate. Such computations can be done routinely today. The quality of results depends primarily on the availability of dynamic material properties and on the material model employed in the code.

Table I. Computations versus Experiments

Constraints	Computer Simulation	Field Experiments
Cost	Typical 3D simulation costs ∿\$6000 for penetration simulation. Typical 2D (plane strain) simulation costs ∿\$1500.	Typical cost for one shot is \$7500 (including materials and fabrication costs and data reduction).
Time	Up to one week may be needed to grid and debug problem, several weeks to obtain and analyze results.	Once materials have been fabricated, one to two shots per day can be obtained.
Information	Maximal output - displacements, stress, strain, strain rate, momenta, energies, forces and moments.	Minimal - initial and final velocity and orientation for projectile; residual projectile mass; target hole size and mass loss.
Unknowns	Results depend on material model, material properties, failure model.	Uncertainties in material properties, initial conditions and boundary conditions manifested as data scatter.
Utility	Excellent base for construction of approximate analytical models for parametric studies.	Time and cost constraints almost never permit acquisition of data base with enough variation of parameters to construct unambiguous models.

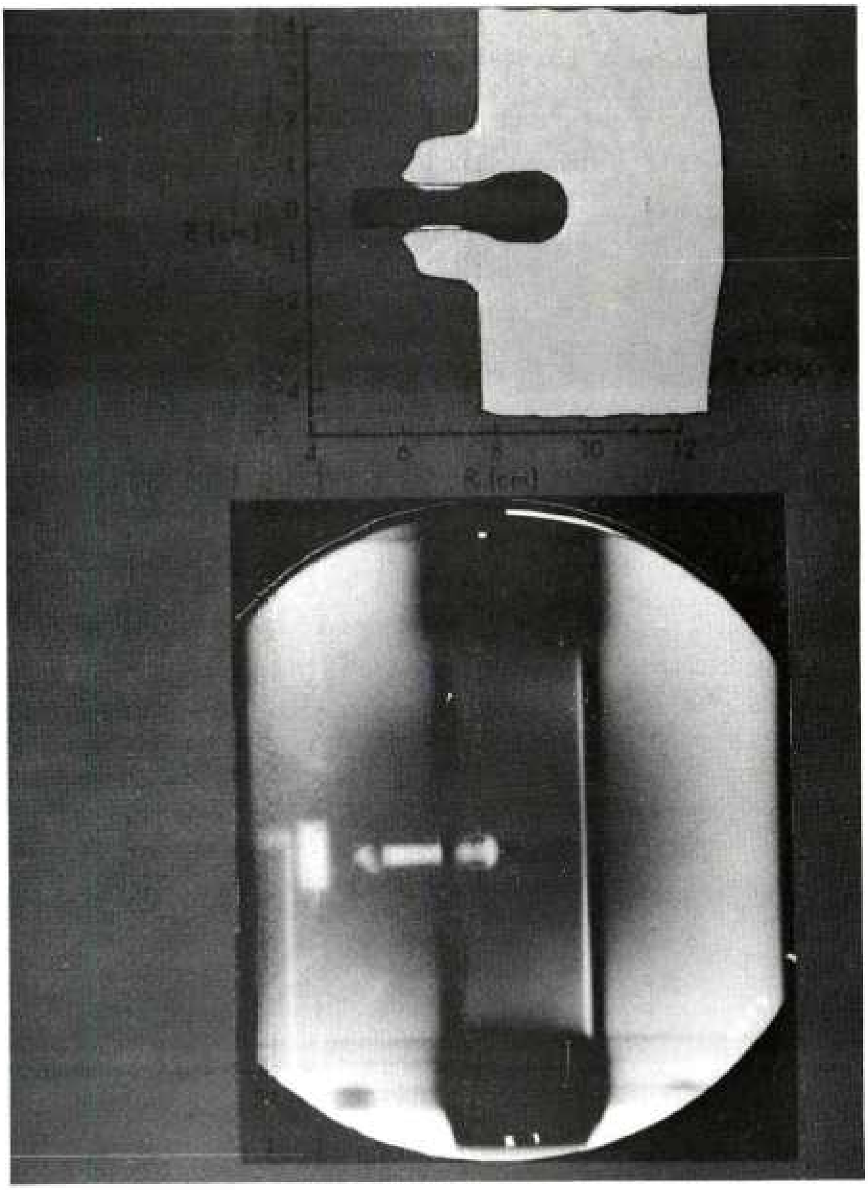

Figure 1. Penetration Profiles for Axisymmetric Impact at 50 Microseconds

Oblique impact, however, is clearly the problem of greater practical importance in the design of projectiles and evaluation of their effectiveness. Oblique incidence is a three-dimensional problem, i.e., the geometry involves specification of three space coordinates. There are pitifully few analytical models[1] which treat oblique incidence and these tend to be extremely simple while also relying heavily on empirical input. Hence recourse is frequently made to 3D numerical solutions and 2D plane strain approximations.

Three-dimensional codes, both finite element and finite difference, exist and have been used successfully to study problems involving penetration, ricochet, crack propagation and the like[1,4,5]. However, they make severe demands on computer storage and are quite costly, although this latter aspect will become less of a problem with the advent of the next generation of computers. The codes at present are invaluable for phenomenological studies but are not yet working tools for designers working in the area of ballistic impact.

Two-dimensional plane strain calculations are straightforward enough, relatively inexpensive and provide some interesting information. However, when oblique impact of a long rod penetrator is treated as the impact of an infinitely long wedge (Figure 2), important physical phenomena are being neglected, i.e., the out-of-plane motions leading to lateral stress relaxations. Useful qualitative information (and, as will be shown, limited quantitative information) about the early stages of an oblique impact can be obtained from plane strain solutions. Their utility, however, degrades with increasing time after impact so that for late times, when important aspects of penetration and target response (i.e., bending, shear failure) are being determined, plane strain solutions are speculative at best.

III. RESULTS

Several calculations were undertaken to obtain a better appreciation of the utility of plane strain approximations. The first set involved the multi-material projectile of Figure 3, a long rod consisting of a maraging steel sheath and tungsten alloy core. Computations were made with the HELP code in both the axisymmetric and plane strain modes with the projectile striking a 2.37 cm RHA target at 0° with a velocity of 1.45 km/s. The second set involved the impact of a 65 gram, L/D = 10, hemispherical nose, staballoy penetrator against a 1.91 cm RHA plate at 60° obliquity with a striking velocity of 1.5 km/s.

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[4] *Johnson, G. R., "A New Computational Technique for Intense Impulsive Loads," Proc. 3d Intl. Symp. on Ballistics, Karlsruhe, Germany, March 1977.*

[5] *Chen, Y. M., "Numerical Solutions of Three-Dimensional Dynamic Crack Problems and Simulation of Dynamic Fracture Phenomena by a 'Non-Standard' Finite Difference Method," Engr. Fract. Mech., V10, pp. 699-708, 1978.*

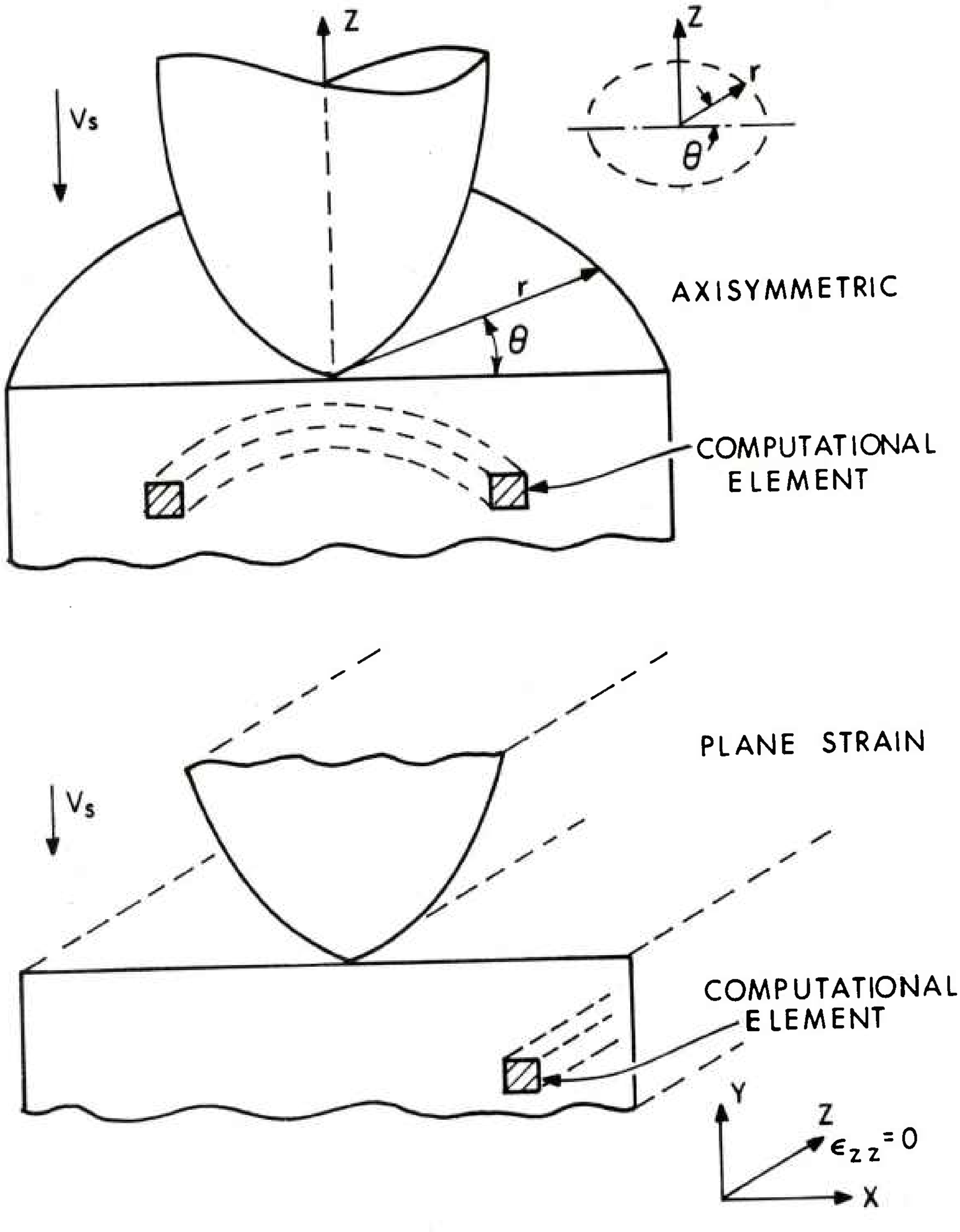

Figure 2. Computational Elements for Axisymmetric and Plane Strain Calculations

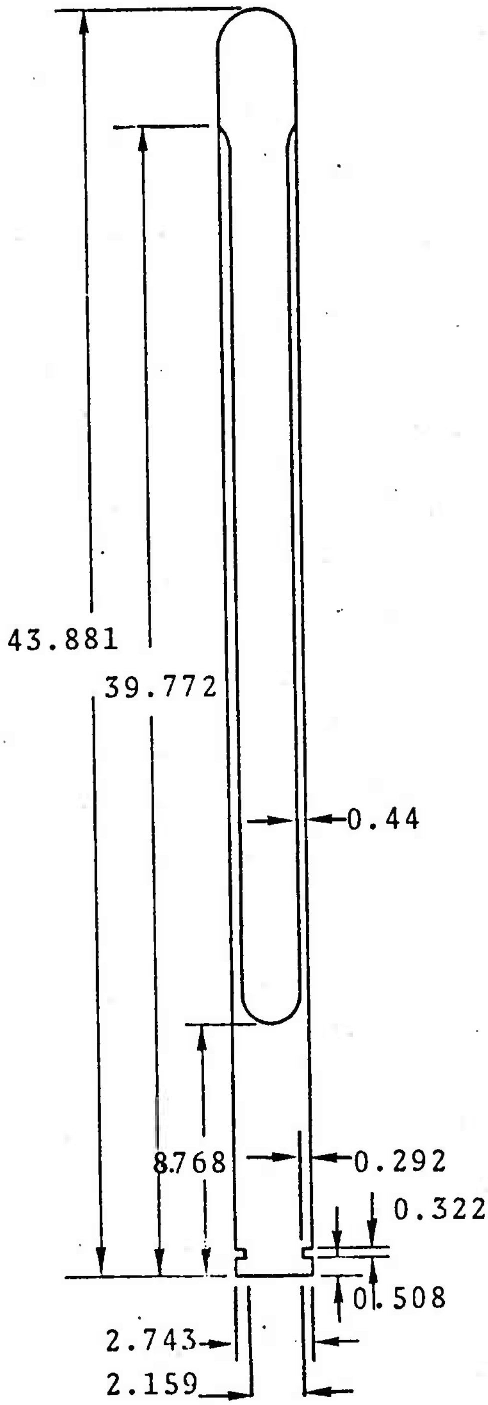

Figure 3. Multi-material Penetrator (units in cm)

All computational results were obtained with the HELP code, a two-dimensional, multi-material Eulerian code for solving material flow problems in the hydrodynamic and elasto-plastic regimes. Although the code is basically Eulerian, material interfaces and free surfaces are propagated in a Lagrangian manner through the calculational mesh as discrete interfaces across which material is not allowed to diffuse. The material model employed in HELP includes the Tillotson equation of state[6], modified to give a smooth transition between condensed and expanded states, a deviatoric constitutive relation, a yield criterion defined to account for the increase in strength at high compressions and decrease with increases in internal energy, and failure criteria. Failure in tension is based on relative volume. When the relative volume in a cell reaches a certain value greater than a specified maximum distension, that cell is said to fail and any computed tensions are zeroed out. Failure can also occur when the internal energy is greater than the melt energy. Material properties used for the computations are given in Table II. The projectile material parameters were obtained from Dr. Ernest Bloore while a member of the Penetration Mechanics Branch and the RHA parameters from the Solid Mechanics Branch, TBD, BRL.

Table II. Material Parameters

Material	E (GPa)	ν	σ_y (GPa)	σ_u (GPa)	ρ (kg/m^3)
Staballoy	195.8	0.203	1.036	1.45	18.62×10^3
90-7-3 tungsten	372.0	0.269	0.553	1.14	17.04×10^3
MAR-M-300 steel	180.7	0.264	1.827	1.945	8.07×10^3
RHA	209.9	0.3	1.220	1.35	7.8×10^3

E - Young's modulus

ν - Poisson's ratio

σ_y - yield strength

σ_u - ultimate strength

ρ - density

Computed deformation profiles for the normal impact multi-material penetrator from the axisymmetric and plane strain computations are shown in the Appendix. Shown also are plots of state variables (kinetic energy,

[6] *Tillotson, J. H., "Metallic Equations of State for Hypervelocity Impact," General Atomic Report GA-3216, July 1962.*

momenta, plastic work, and internal energy) as functions of time. The differences between the exact (axisymmetric) and plane strain cases are readily apparent. Differences between the two computations become quite pronounced with time, as is evident from both the state variable plots and deformation plots. At late times, the plane strain calculation clearly shows greater deformation and failure than the axisymmetric case. The plots of penetrator kinetic energy and axial momentum also indicate a relationship between plane strain and axisymmetric results exists and can readily be found by considering the difference in volumes for the two cases. Denoting by V_p the volume per unit depth of the round under the plane strain approximation (unit thickness slab) and by V_a the actual volume (axisymmetric case), then the kinetic energy and linear momentum of the projectile become coincident upon application of a scaling factor of

$$\lambda = \frac{(V_a/V_p)_{M_1}\,\rho_{M_1} + (V_a/V_p)_{M_2}\,\rho_{M_2}}{\rho_{M_1} + \rho_{M_2}} \qquad (1)$$

where ρ represents density and M_1 and M_2 refer to the two materials of the composite round. Note that for a single material projectile ($\rho_{M_1} = \rho_{M_2} = \rho$), the scaling factor reduces to

$$\lambda = V_a/V_p \qquad (2)$$

If actual dimensions are used in (1), one is led to the conclusion that the plane strain velocity should be reduced by $\sim\sqrt{2}$, i.e.,

$$v_p \sim v_a/\sqrt{2} \qquad (3)$$

to achieve comparable energies (and therefore, hopefully, damage levels). This is in agreement with conclusions reached by Bertholf et al[7] who obtained the same expression based on considerations of comparable target damage for the two cases.

The results for the target behavior and for projectile plastic work and internal energy indicate that there is no simple relationship between

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[7] *Bertholf, L. D., Kipp, M. E., Brown, W. T., "Two-Dimensional Calculations for the Oblique Impact of Kinetic Energy Projectiles with a Multi-Layered Target", BRL-CR-333, March 1977.* (AD #B017358L)

plane strain and exact results for these state variables, and that considerable additional work needs to be done before plane strain calculations can supplant fully three-dimensional calculations in assisting kinetic energy projectile designers, a point made also by others[8,9].

The stated data in the Appendix also shows that, for sufficiently energetic impacts, which in this case is a projectile at ordnance velocity and considerable higher density than the target, and for short time intervals after impact, good quantitive, as well as qualitative, information may be extracted from plane strain results. Another example of this is the near-perfect agreement between plane-strain results and experiment for deformation fields obtained by Norris et al[10] who were able to establish the mechanisms leading to target defeat and ricochet in long rod impacts. Once the effects of lateral relief waves (not accounted for in plane strain computations) become significant, increasing divergence between plane strain and exact results is to be expected.

Results for the oblique impact computation and their PHERMEX[3] counterpart are shown in Figures 4 through 6. At the later time (Figure 5) they are both surprising and fortuitous considering the underlying differences between the slab approximation and the exact three-dimensional case. It is probable that such excellent agreement can be partially attributed to the tendency of the projectile material (depleted uranium) to erode continuously at the impact end. This computation was repeated with EPIC3, a three-dimensional finite element Lagrangian code[1]. The agreement between experiment, plane strain and three-dimensional results for deformation fields, residual length and velocity is excellent, the measured quantities being within a few percent of each other. Profile comparisons of these three results are shown in Figure 7.

Although at early times agreement for hole profiles and residual length of the penetrator was quite good, it should be noted that the tabular data arising from the computer runs showed spurious signals in the form of small radial velocities within the first microsecond in regions where no genuine signal could have propagated. Also found for the multimaterial penetrator were regions where internal energy and plastic work were negative. These anomalies affect the values of pressure, stress and energy in some areas of the calculation. A more thorough discussion of HELP code problems can be found elsewhere[11]. It can be concluded that although useful results have been obtained with

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[8]*Kipp, M. E. and Bertholf, L. D., private communication.*

[9]*Sedgwick, R. T., Waddell, J., and Hageman, J. L., "A Comparison of Results from Two Long Rod Oblique Impact Calculations," BRL-CR-288, February 1976.* (AD #B009783L)

[10]*Norris, D. M., Scudder, J. K., McMaster, W. A., Wilkins, M. L., "Mechanics of Long Rod Penetration at High Obliquity," in Proc. High Density Alloy Penetrator Materials Conf., AMMRC-SP-77-3, 1977.*

[11]*Jonas, G. H., and Zukas, J. A., "Cap Design for Kinetic Energy Penetrators," BRL-R-1813, August 1975.* (AD #B006902L)

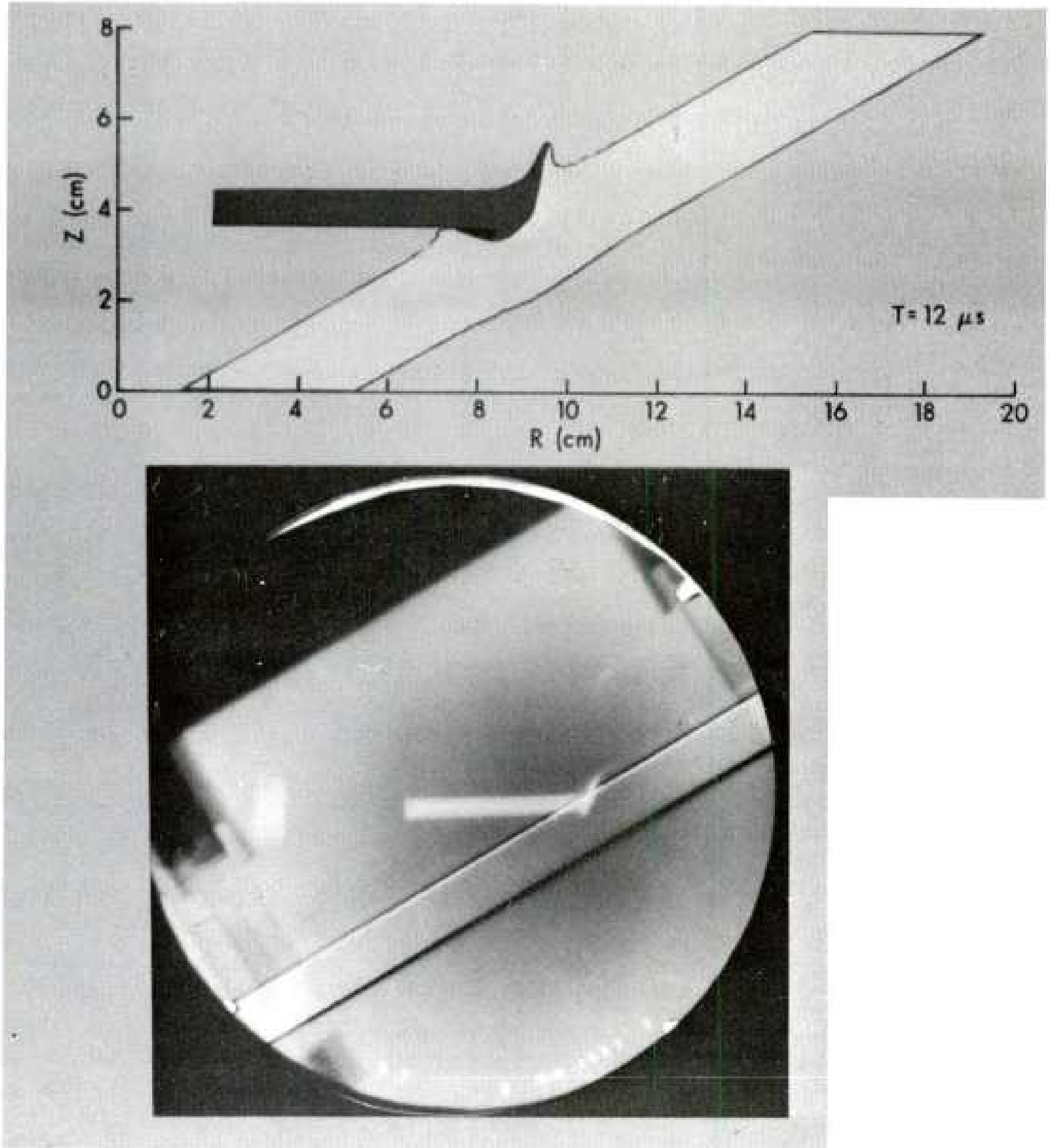

Figure 4. Comparison of Plane Strain and Experimental Results at 12 Microseconds

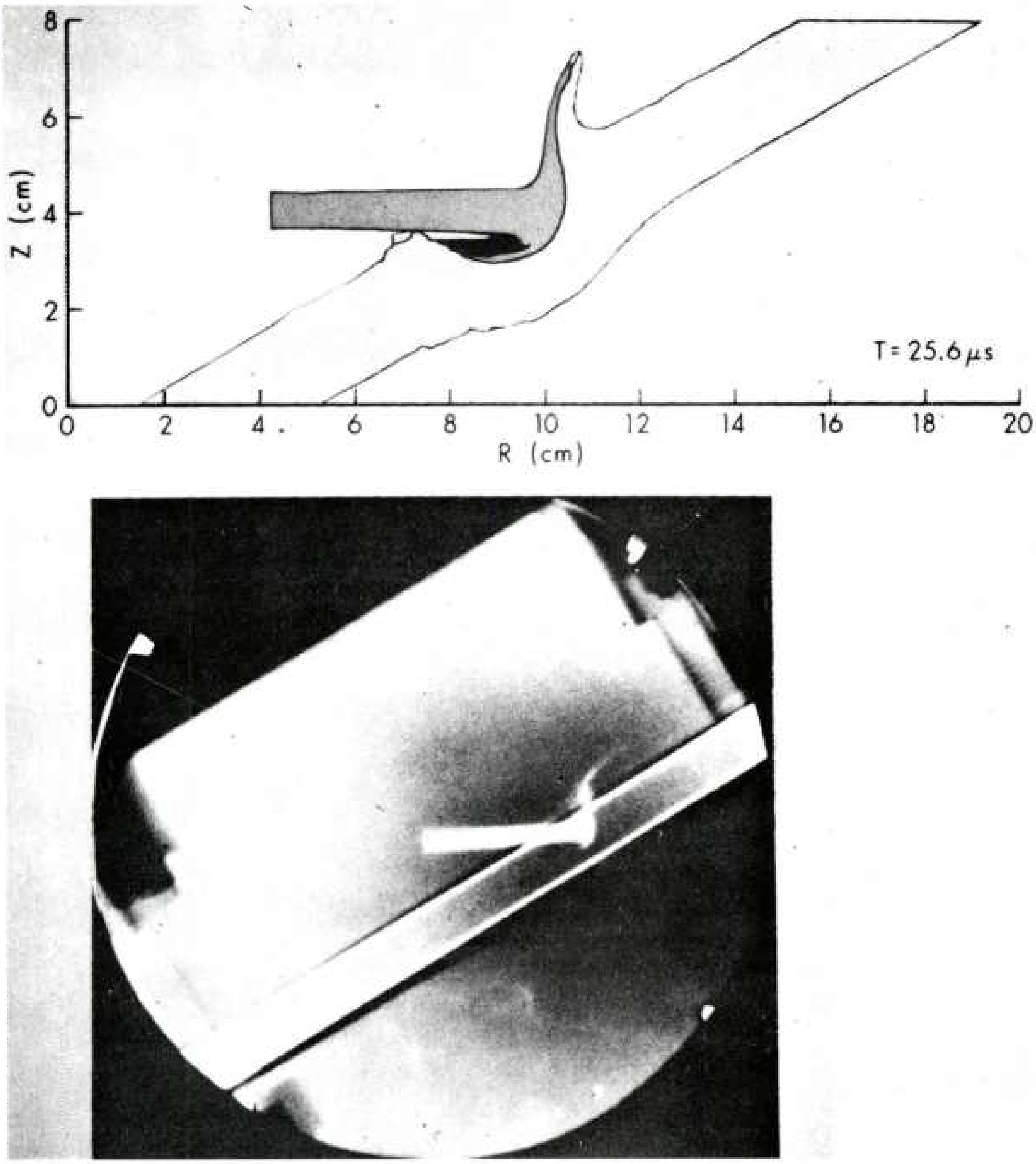

Figure 5. Comparison of Plane Strain and Experimental Results at 25.6 Microseconds

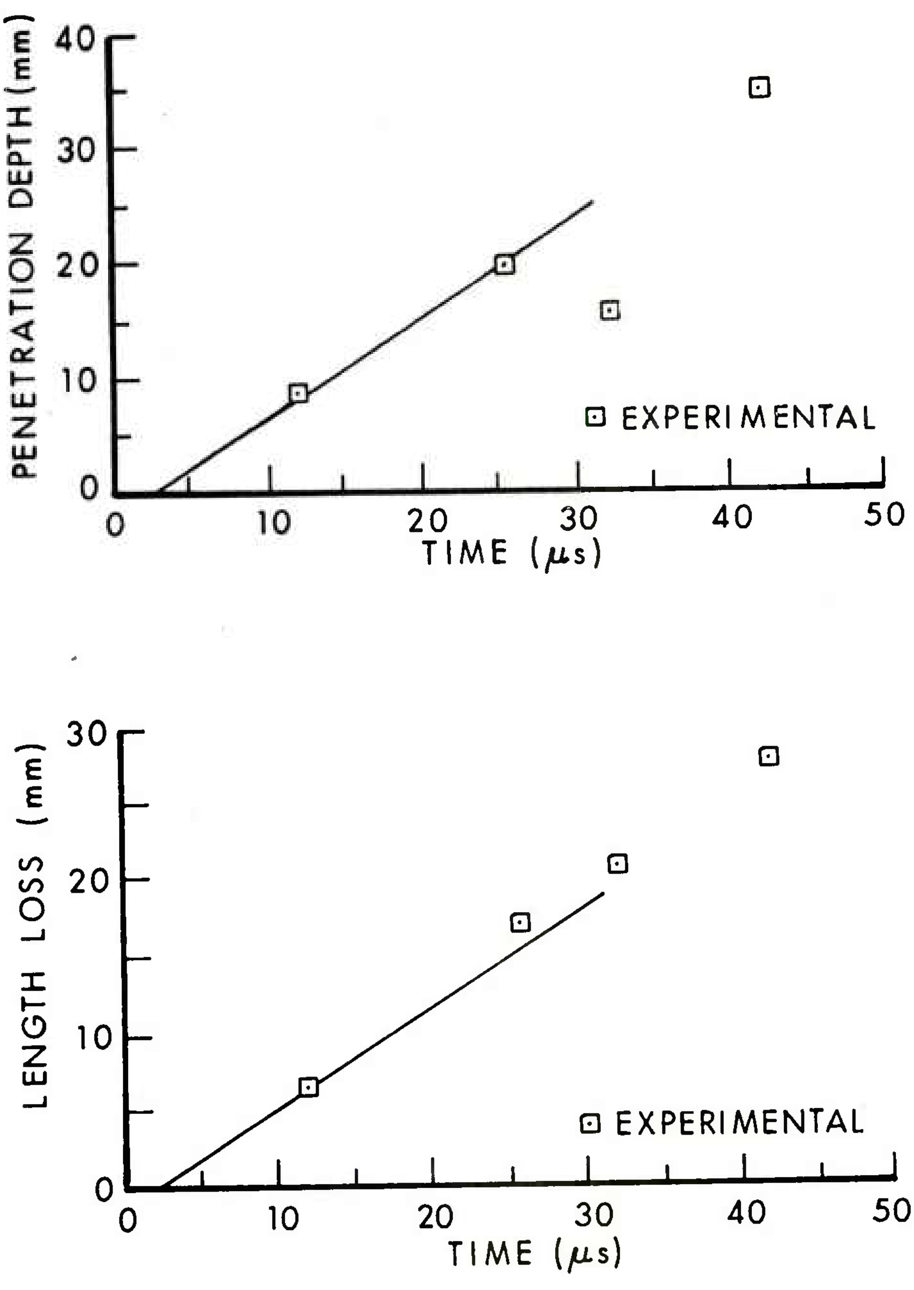

Figure 6. Penetration Depth and Rod Loss vs. Time for 60° Oblique Impact

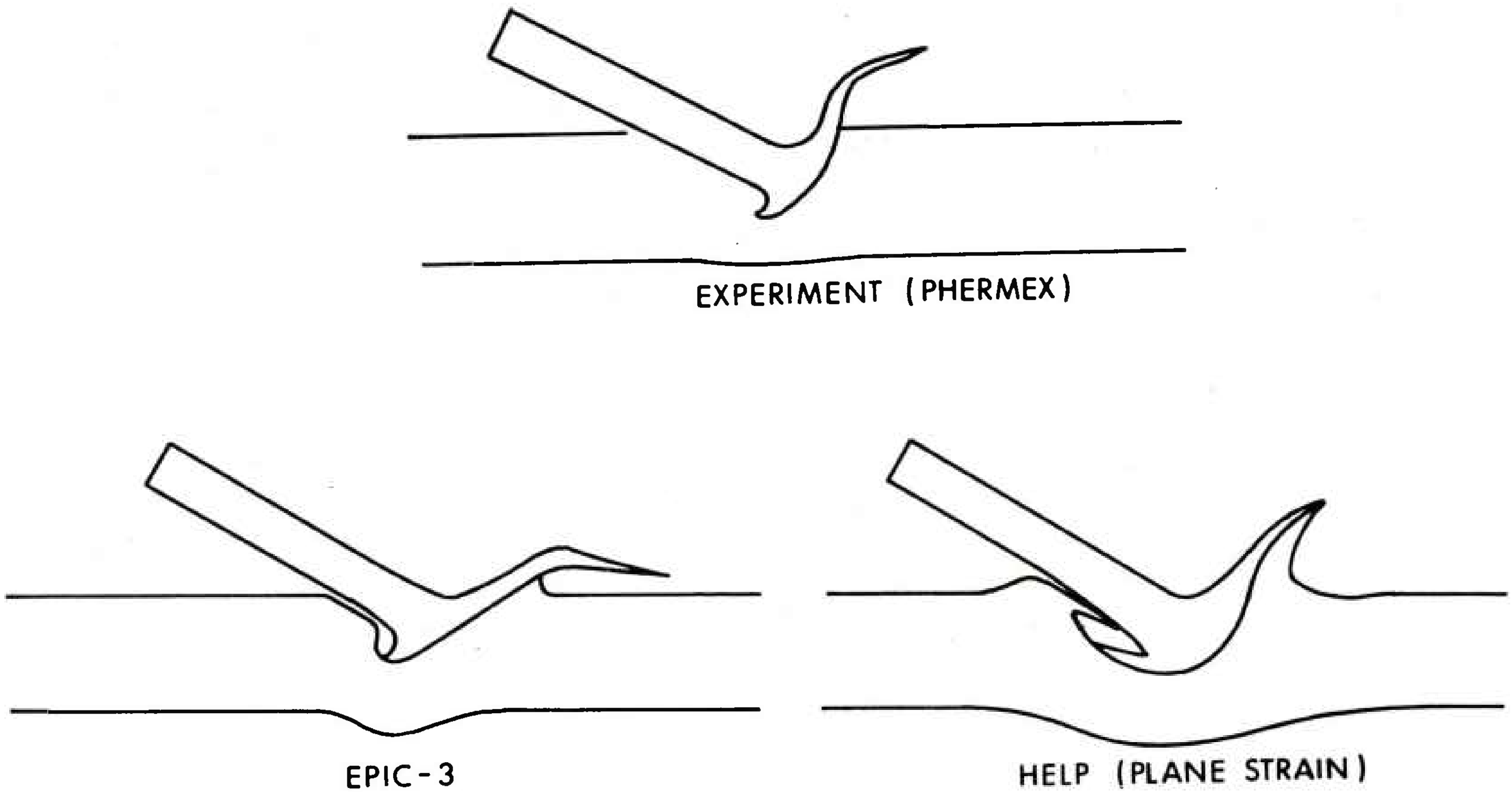

Figure 7. Comparison of Experimental Three-Dimensional and Plane Strain Results at 25 Microseconds

HELP, the code is essentially unreliable in its present form for ordnance velocity impacts. It also requires excessive human intervention for readjusting tracer points, correcting pure cell problems and other anomalies during long computations. A reformation of the basic equations to make them second-order accurate might do much to enhance the code's stability and utility.

IV. CONCLUSIONS

Based on the results shown here and the findings of other researchers, we may conclude that a fair amount of qualitative insight may be obtained from plane strain simulation of oblique impact phenomena and such studies, with suitable caution, can be profitably employed for parametric studies. At sufficiently early times after impact, reasonable quantitative results for deformation and projectile orientation can be obtained. However, for computation of local variables (stress, strain, temperature), recourse must be made to three-dimensional calculations. These in turn will be useful only if the materials in question have been adequately characterized at the strain rates in question.

Additional work needs to be done to relate plane strain to exact results in order to make plane strain computational results useful to projectile and armor designers. Since the cost of plane strain computations is some one-quarter those for three-dimensional calculations, the incentive for such work should be self-evident.

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1. Jonas, G. H. and Zukas, J. A., "Mechanics of Penetration: Analysis and Experiment," Int. J. Eng. Sci., V16, pp. 879-903, 1978.

2. Hageman, L. J., Wilkins, D. E., Sedgwick, R. T. and Waddell, J., "HELP, a Multi-Material Eulerian Program for Compressible Fluid and Elastic-Plastic Flows in Two Space Dimensions and Time, Revised Edition," Systems, Science and Software, SSS-R-75-2654, Topical Report, July 1975.

3. Printed Communication from E. Fugleso, J. W. Taylor and L. W. Hantel of Los Alamos Scientific Laboratory.

4. Johnson, G. R., "A New Computational Technique for Intense Impulsive Loads," Proc. 3d Intl. Symp. on Ballistics, Karlsruhe, Germany, March 1977.

5. Chen, Y. M., "Numerical Solutions of Three-Dimensional Dynamic Crack Problems and Simulation of Dynamic Fracture Phenomena by a 'Non-Standard' Finite Difference Method," Engr. Fract. Mech., V10, pp. 699-708, 1978.

6. Tillotson, J. H., "Metallic Equations of State for Hypervelocity Impact," General Atomic Report GA-3216, July 1962.

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8. Kipp, M. E. and Bertholf, L. D., private communication.

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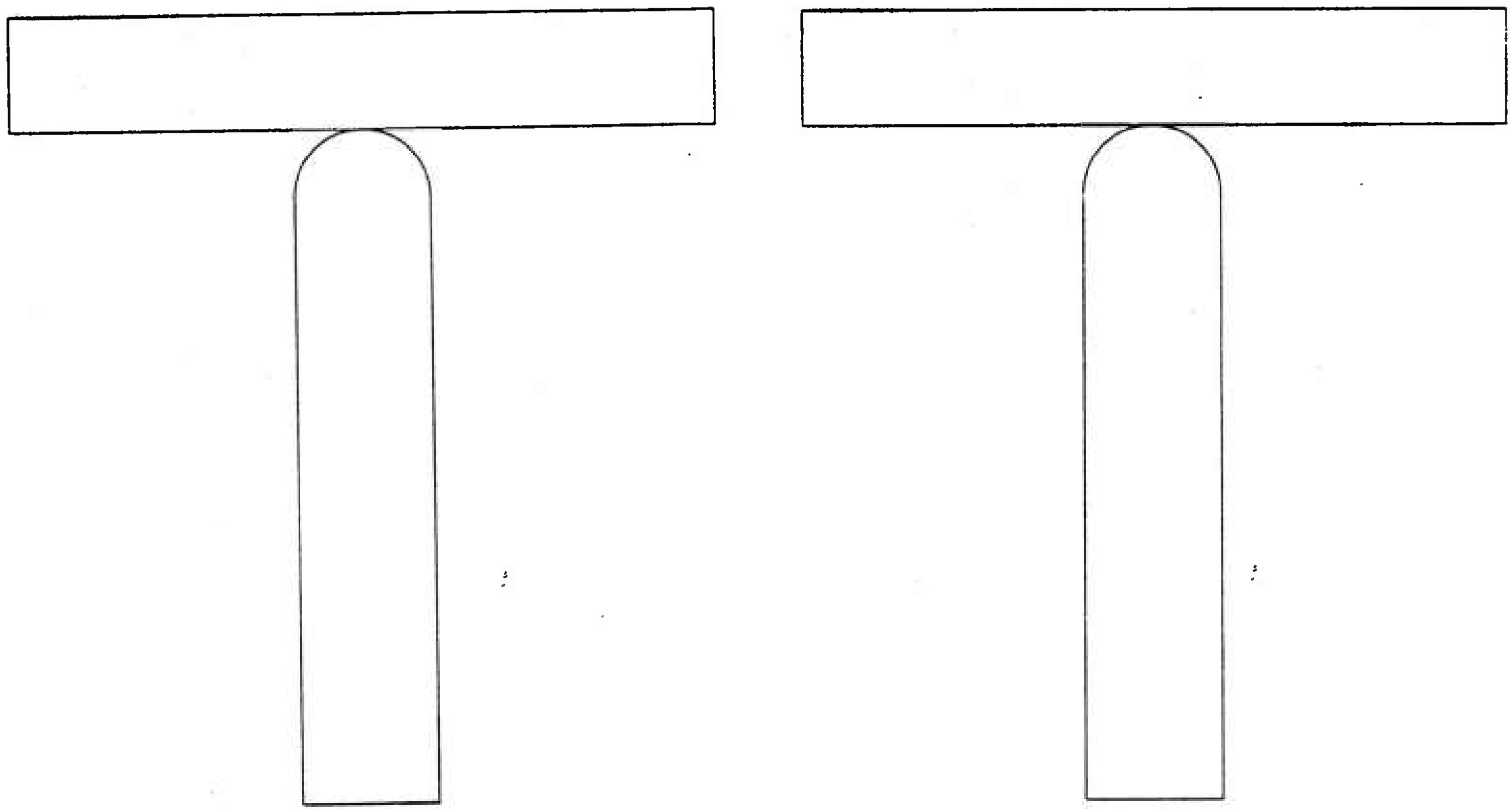
10. Norris, D. M., Scudder, J. K., McMaster, W. A. and Wilkins, M. L., "Mechanics of Long Rod Penetration at High Obliquity," in Proc. High Density Alloy Penetrator Materials Conf., AMMRC-SP-77-3, 1977.

11. Jonas, G. H. and Zukas, J. A., "Cap Design for Kinetic Energy Penetrators," BRL-R-1813, August 1975. (AD #B006902L)

APPENDIX
AXISYMMETRIC/PLANE STRAIN COMPARISONS

The following pages consist of deformation profile plots and graphs of the state variables as functions of time for the axisymmetric and plane strain calculations of a normal impact by a long rod consisting of a maraging steel sheath and tungsten alloy core against a 2.37 cm RHA target at 1.45 km/s. It should be noted that the HELP code being Eulerian is set up with a computational grid in which the material passes through the cells. Because of limited storage the grid is set up so that there is a fine zone where most of the activity occurs and a coarser grid elsewhere. Deformation plots can be obtained either in actual dimensions or cell dimensions. The choice of cell dimensions was made for a clearer picture of what is happening at the interface. For each failed cell an x is placed in that cell. Furthermore, the option was made to draw only the exterior of the projectile.



Axisymmetric   Plane Strain

Figure A-1. Penetrator/Target Profiles at 0 Microseconds for Axisymmetric and Plane Strain Cases

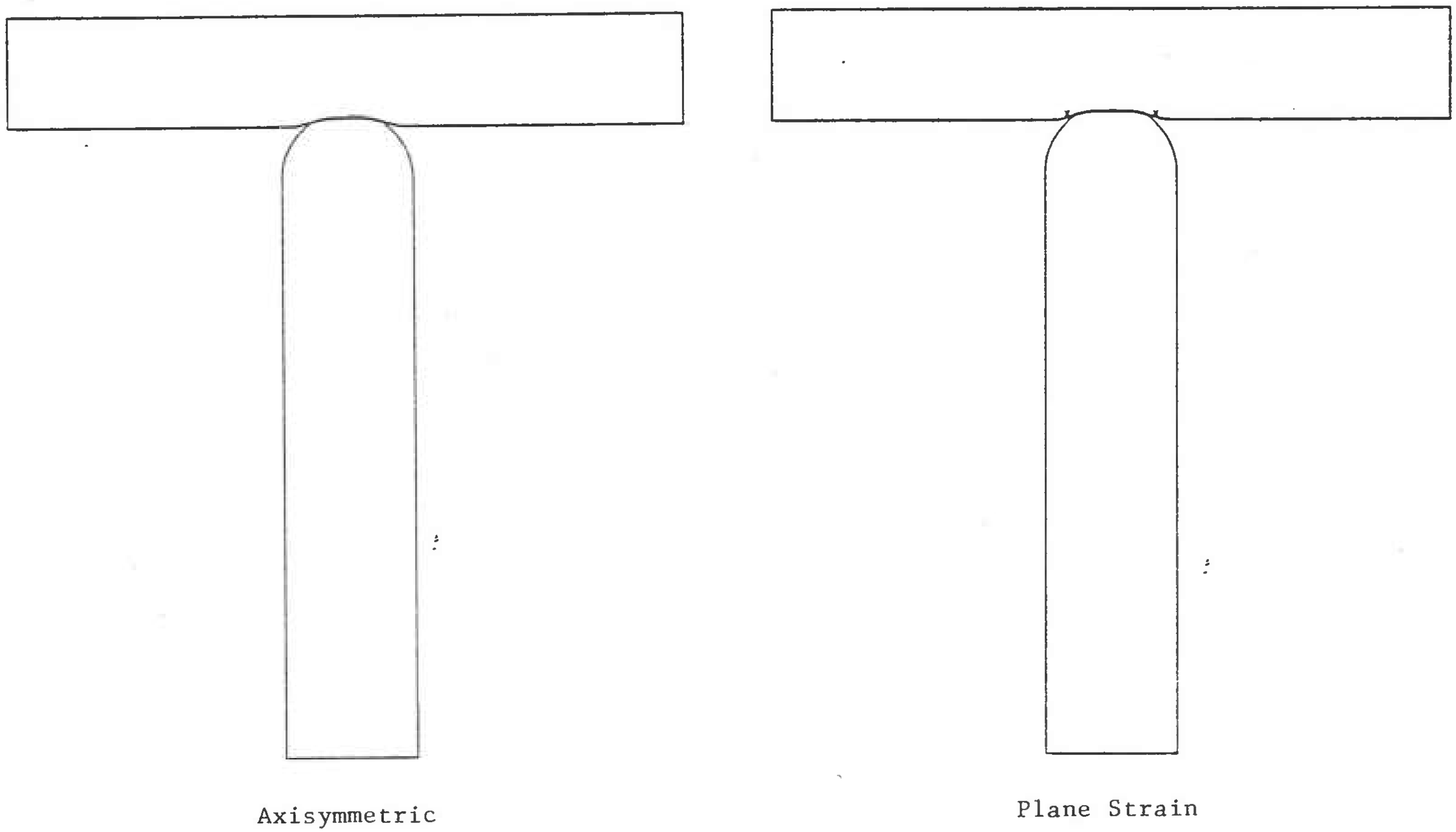
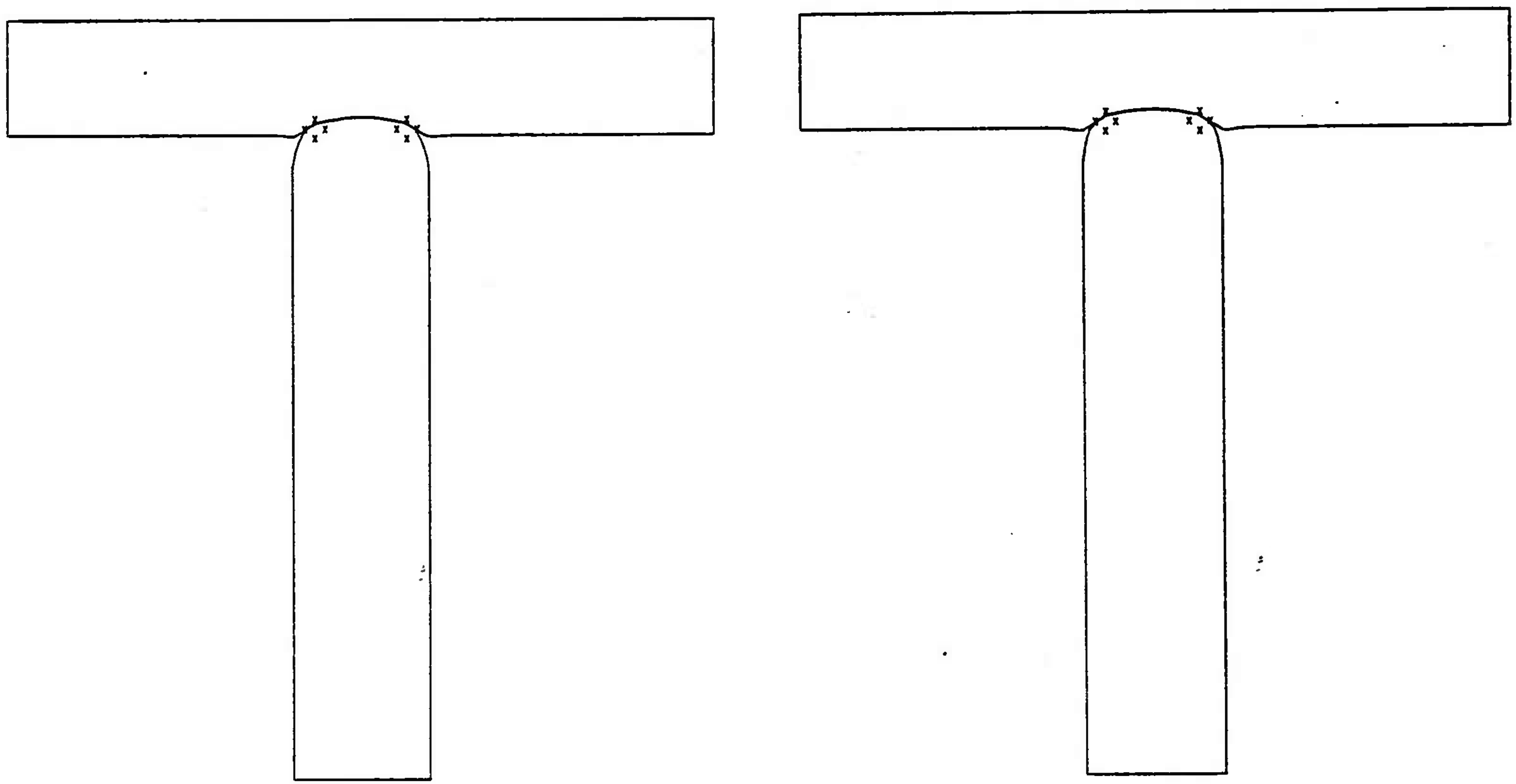


Figure A-2. Penetrator/Target Profiles at 2 Microseconds for Axisymmetric and Plane Strain Cases



Axisymmetric

Plane Strain

Figure A-3. Penetrator/Target Profiles at 4 Microseconds for Axisymmetric and Plane Strain Cases

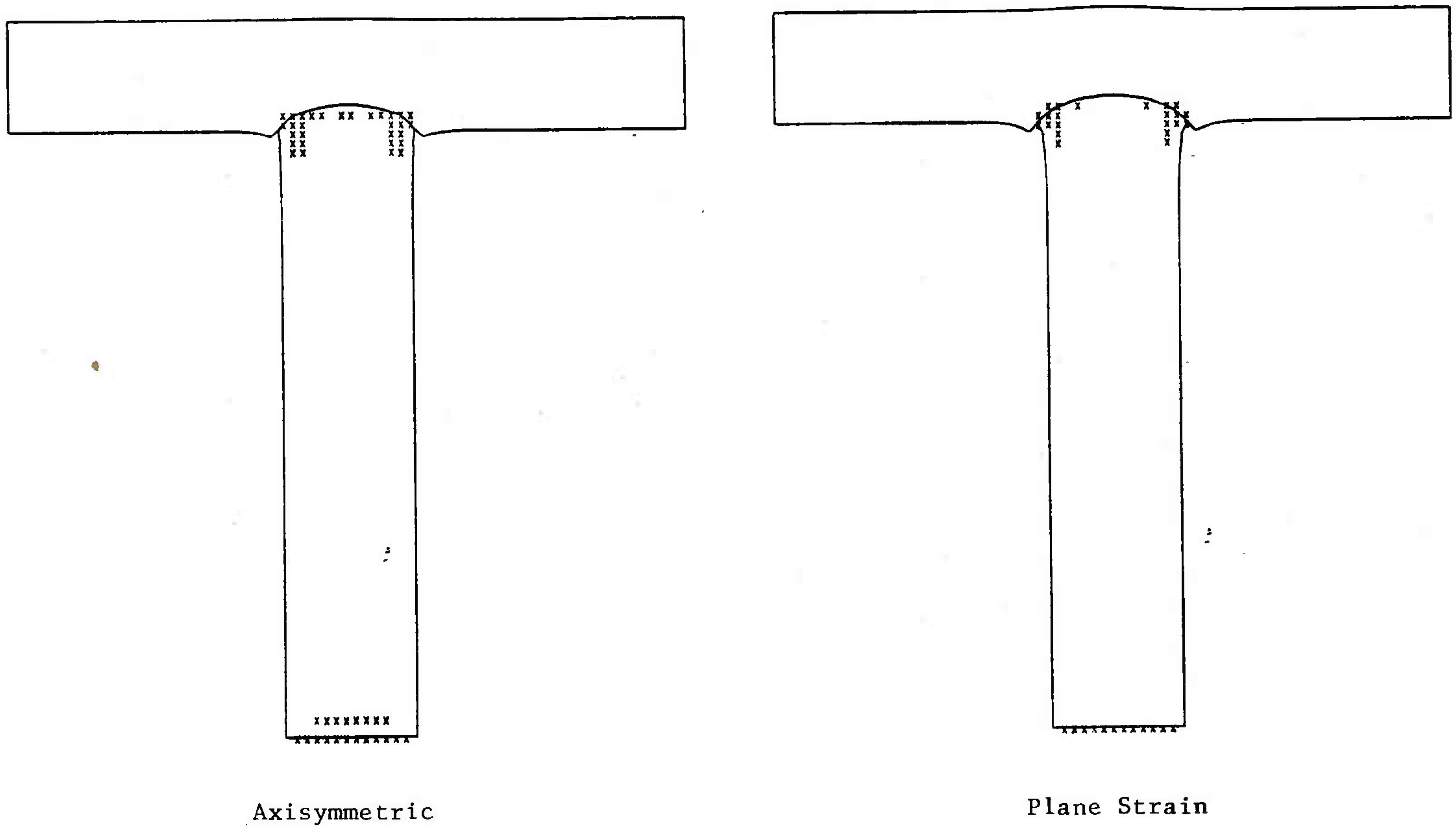


Figure A-4. Penetrator/Target Profiles at 6 Microseconds for Axisymmetric and Plane Strain Cases

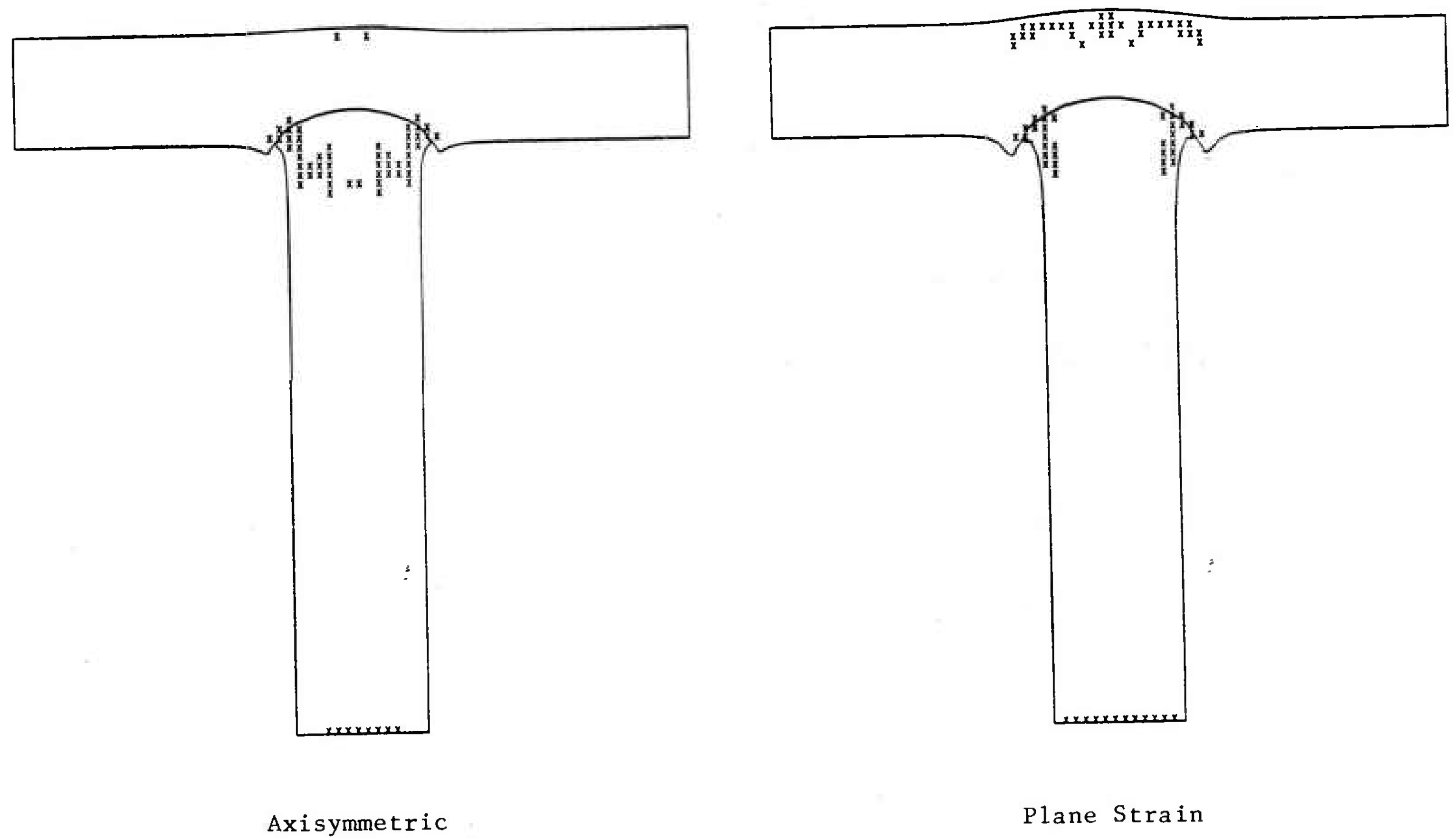
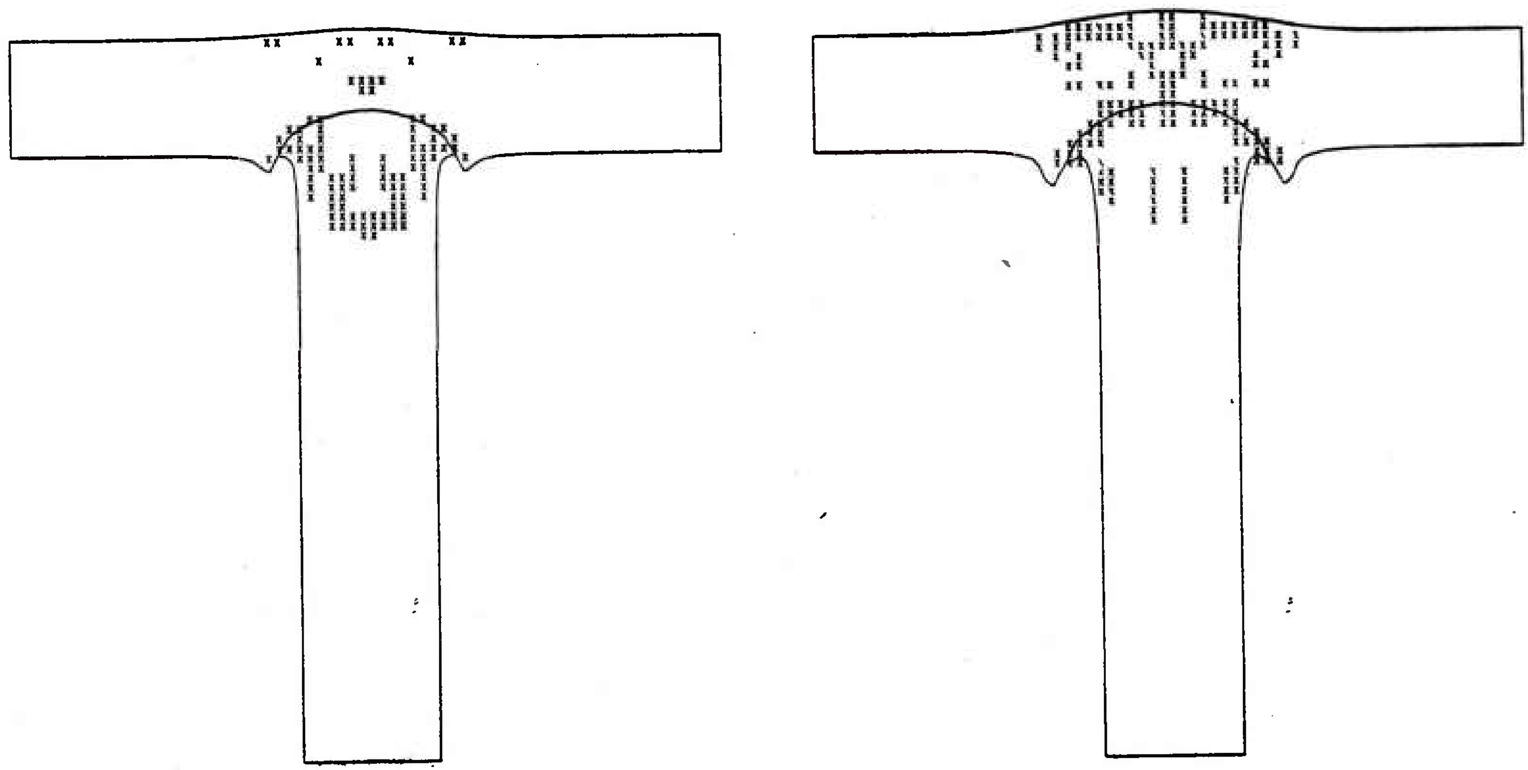


Figure A-5. Penetrator/Target Profiles at 8 Microseconds for Axisymmetric and Plane Strain Cases



Axisymmetric

Plane Strain

Figure A-6. Penetrator/Target Profiles at 10 Microseconds for Axisymmetric and Plane Strain Cases

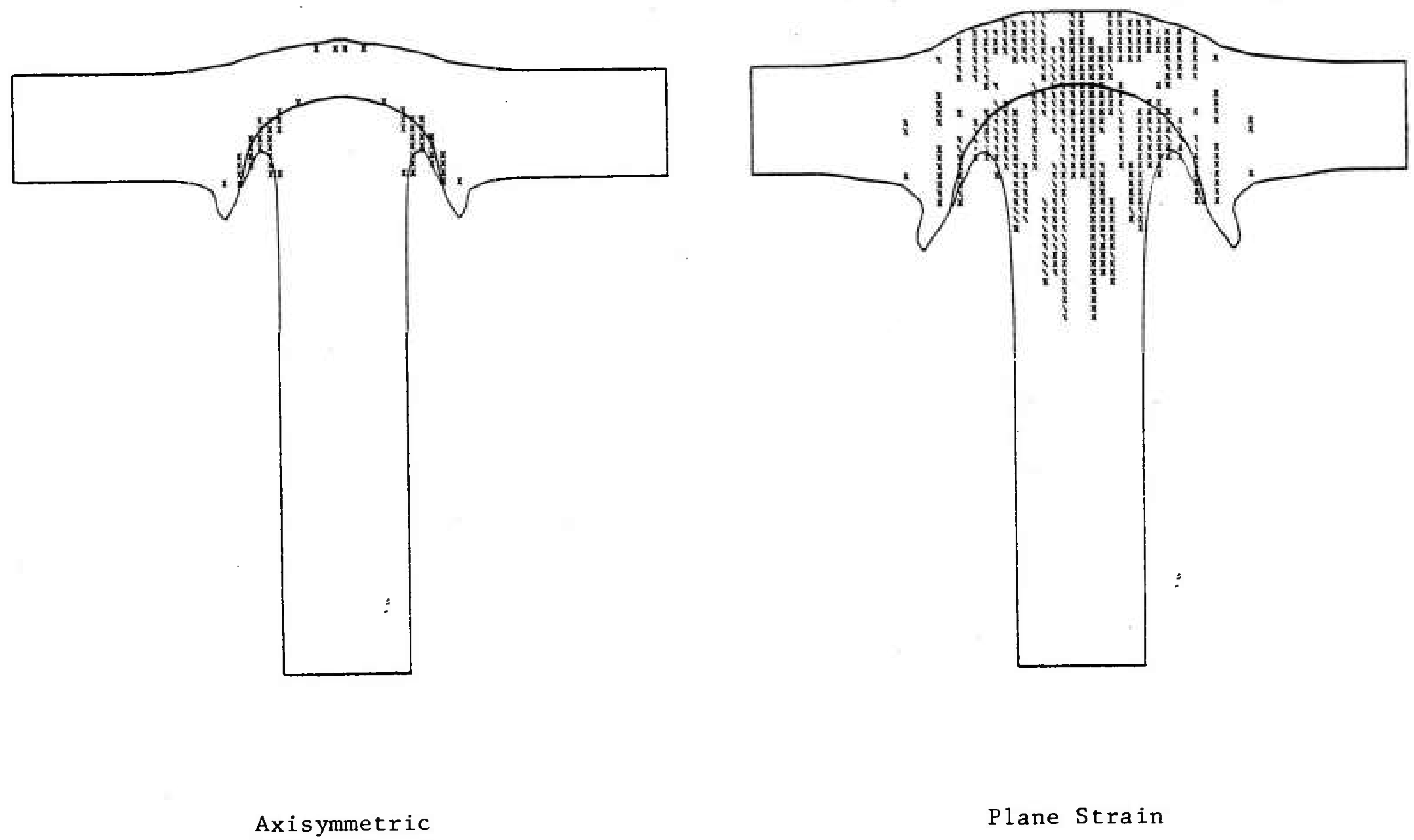
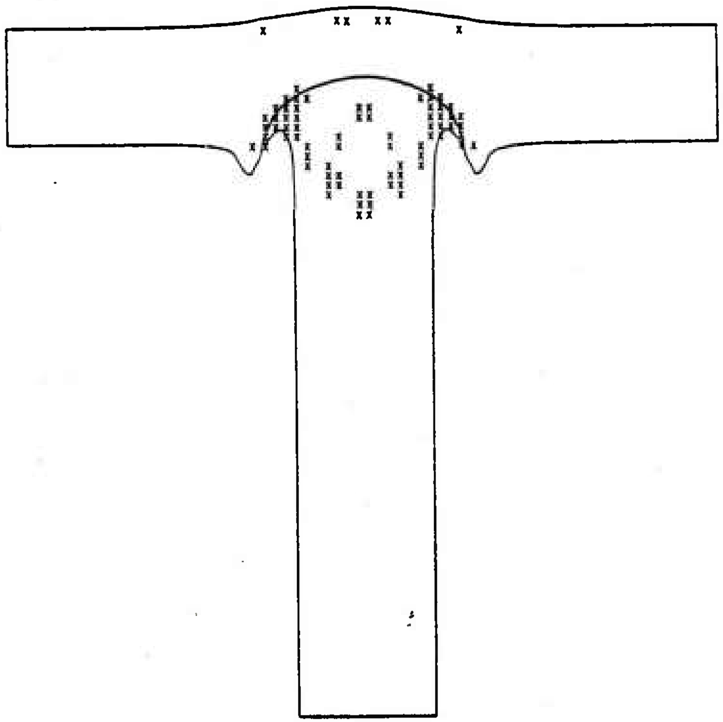
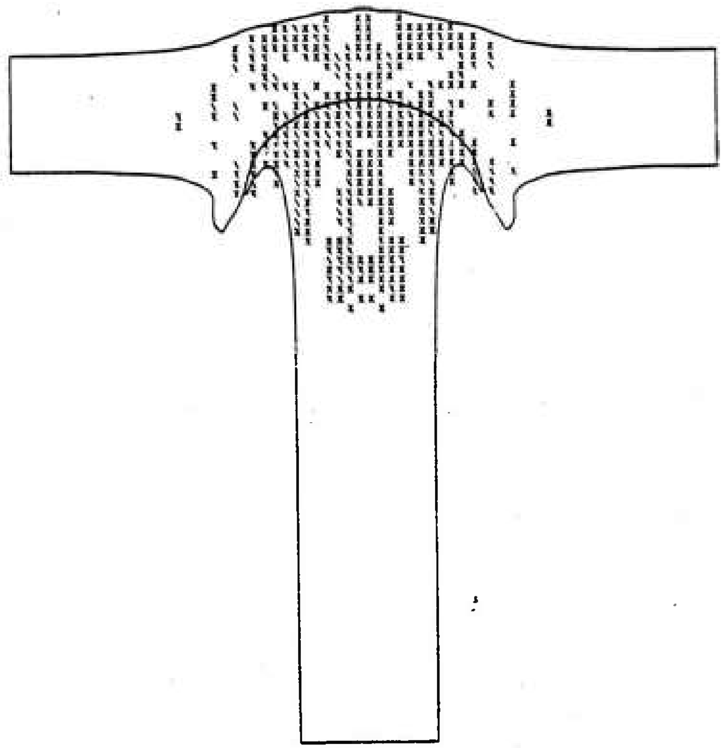


Figure A-7. Penetrator/Target Profiles at 15 Microseconds for Axisymmetric and Plane Strain Cases



Axisymmetric



Plane Strain

Figure A-8. Penetrator/Target Profiles at 20 Microseconds for Axisymmetric and Plane Strain Cases

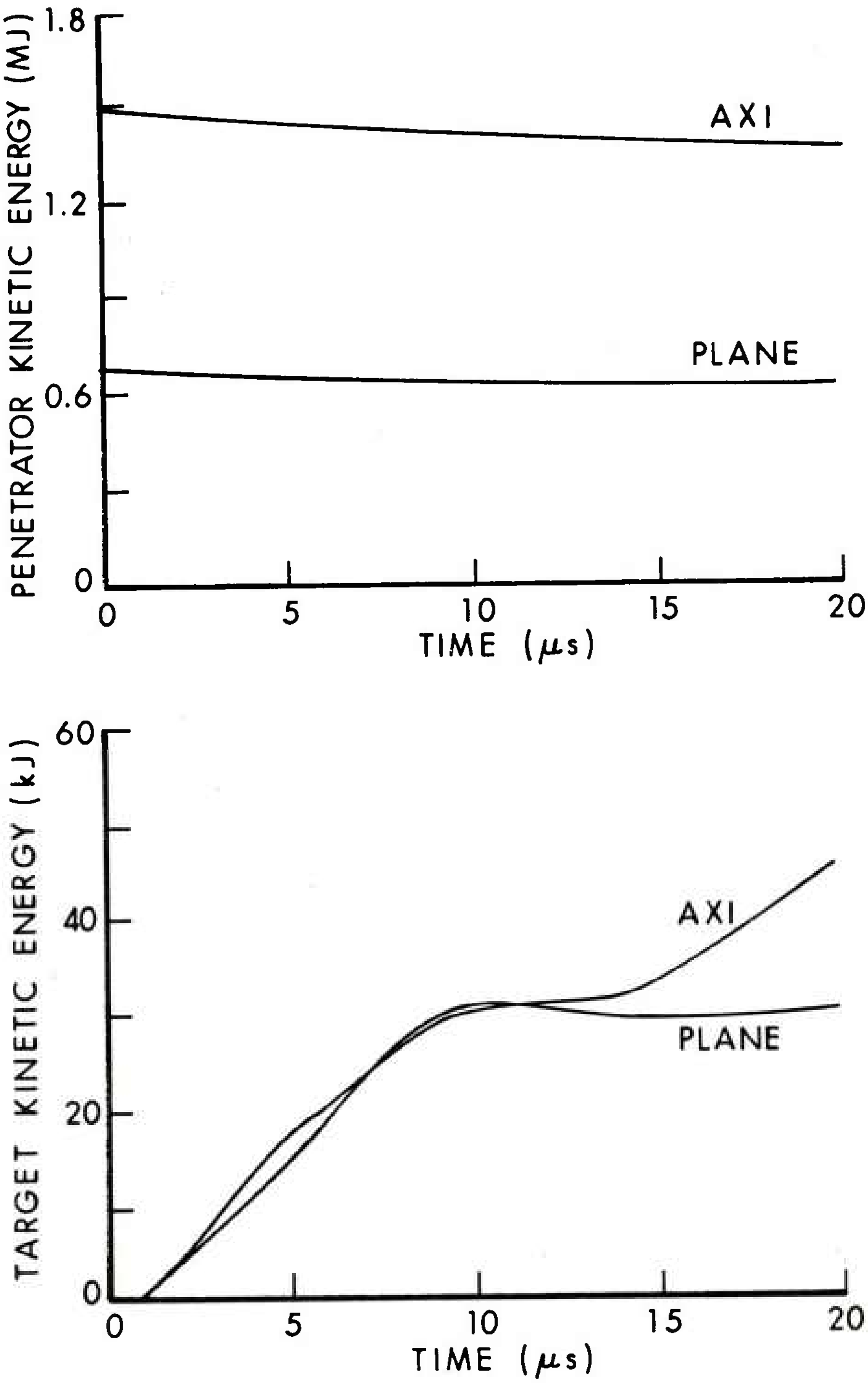


Figure A-9. Penetration and Target Kinetic Energy as a Function of Time for the Axisymmetric and Plane Strain Mode Calculations

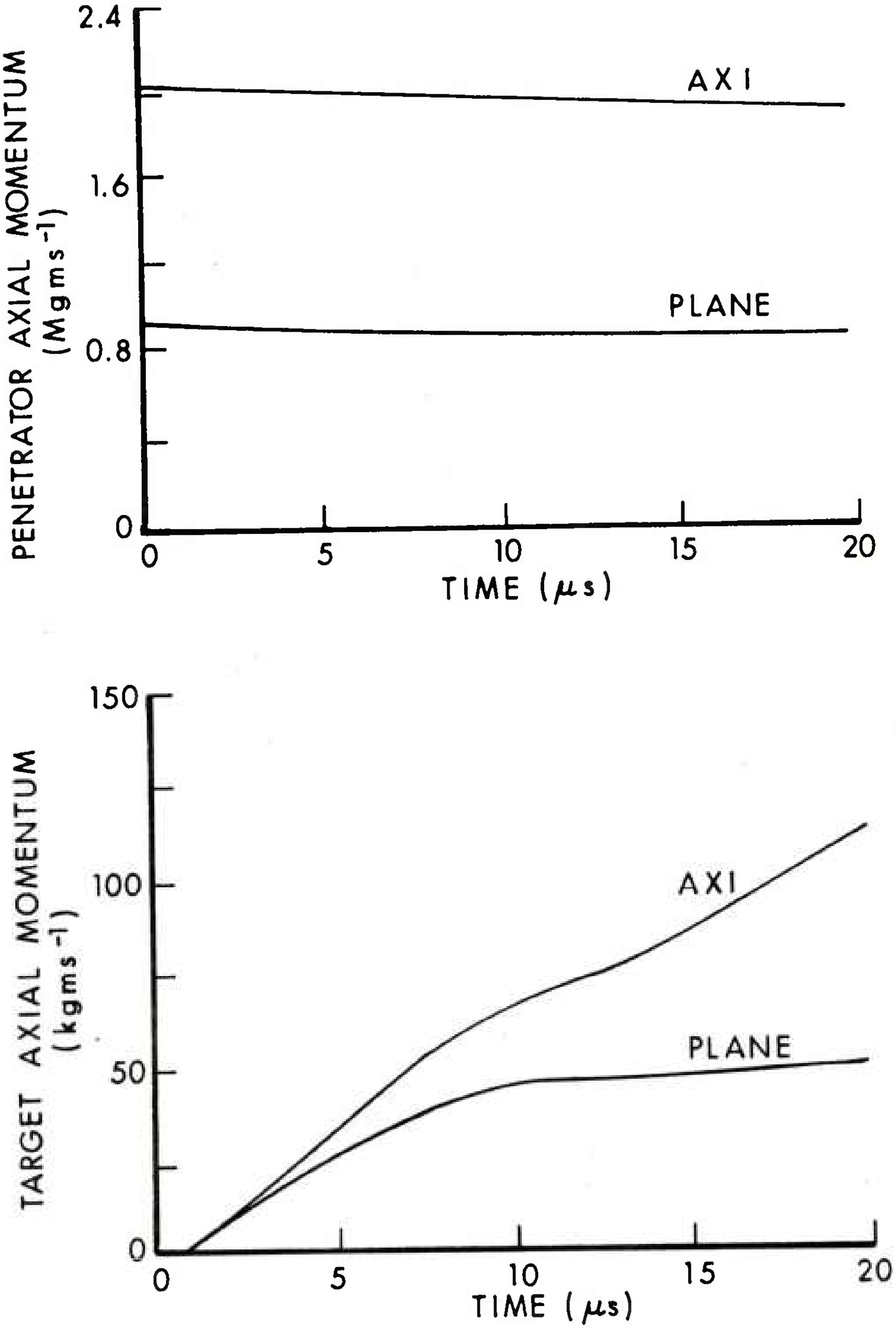


Figure A-10. Penetration and Target Axial Momentum as a Function ot Time for the Axisymmetric and Plane Strain Mode Calculations

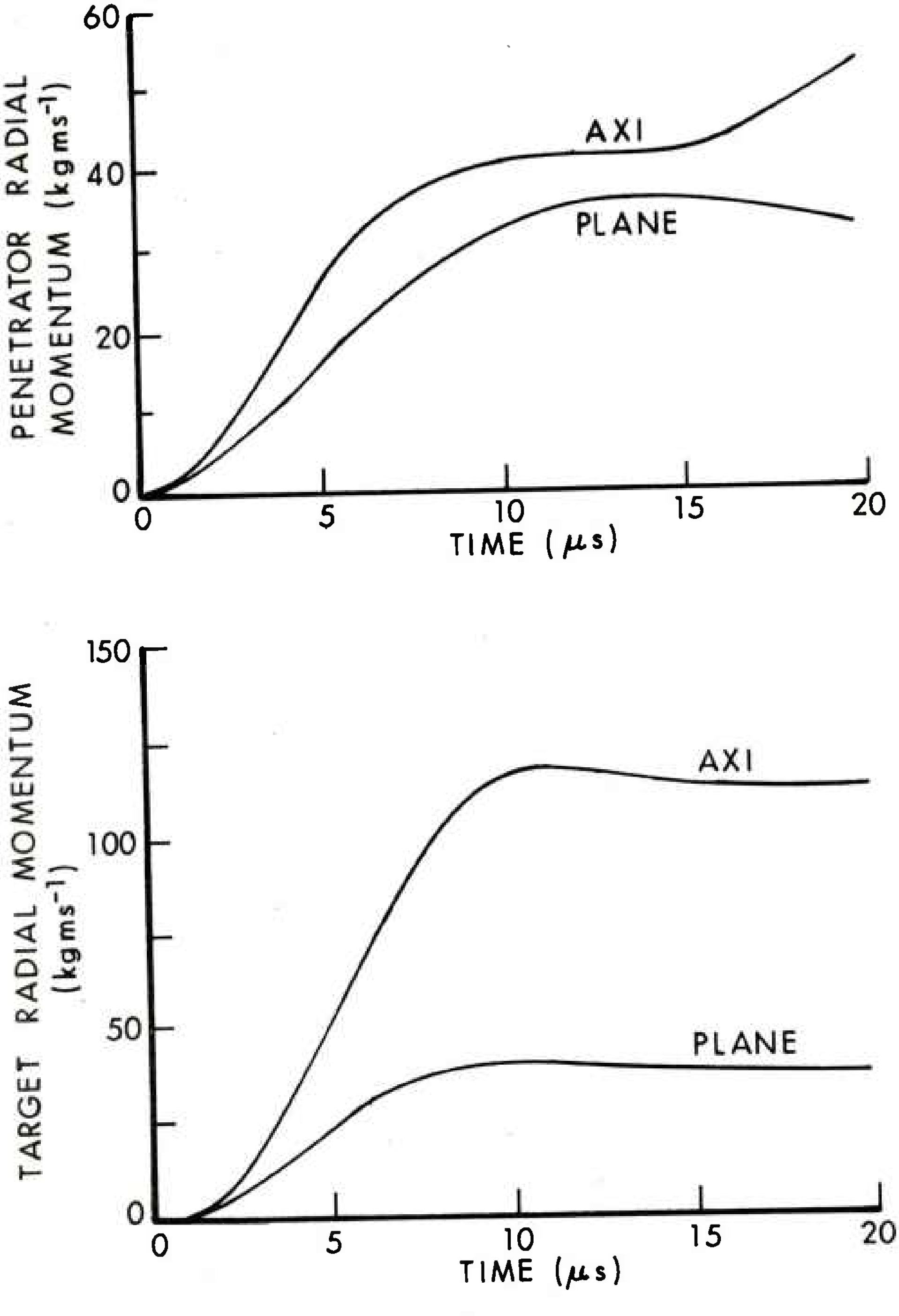


Figure A-11. Penetration and Target Radial Momentum as a Function of Time for the Axisymmetric and Plane Strain Mode Calculations

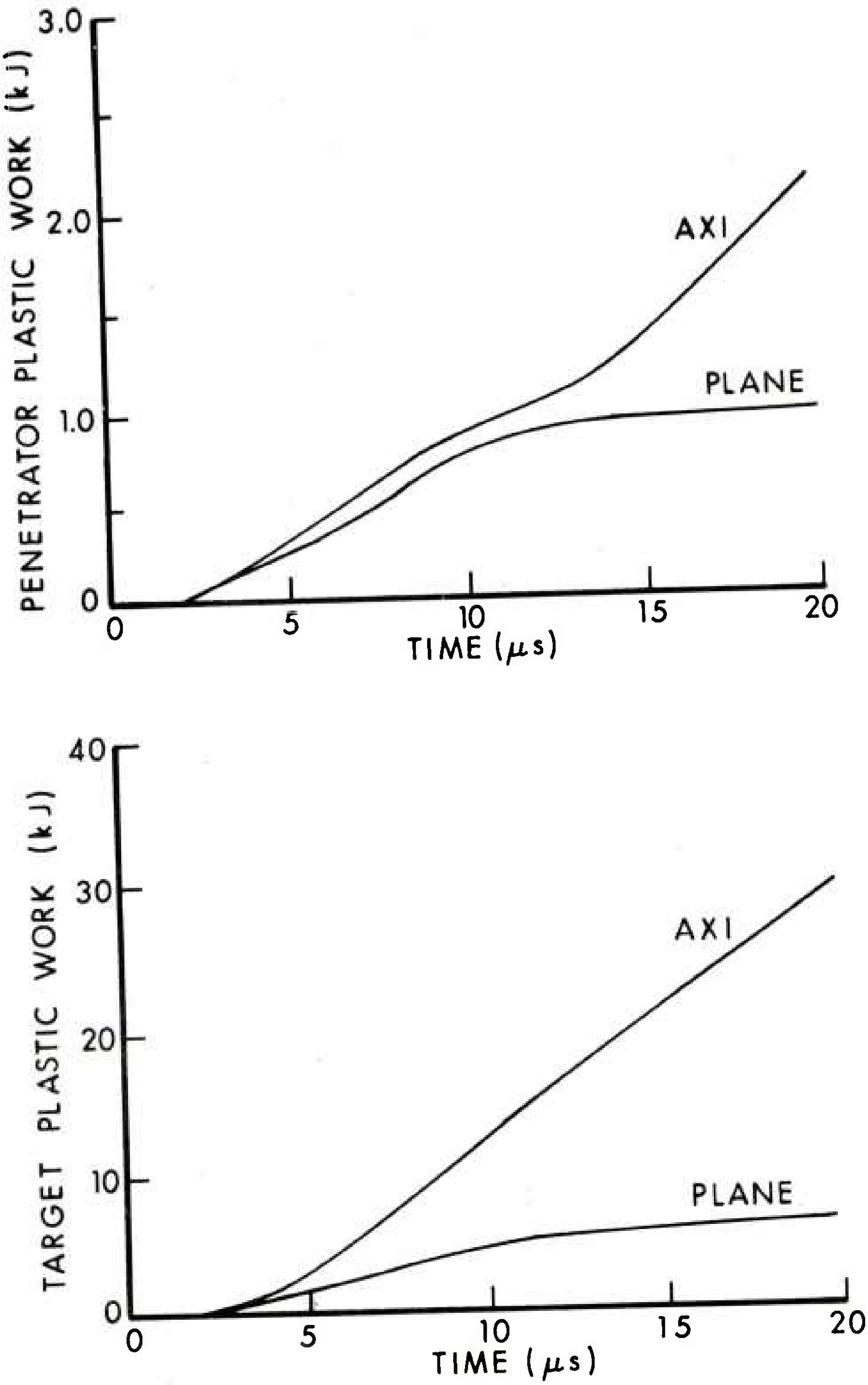


Figure A-12. Penetration and Target Plastic Work as a Function of Time for the Axisymmetric and Plane Strain Mode Calculations

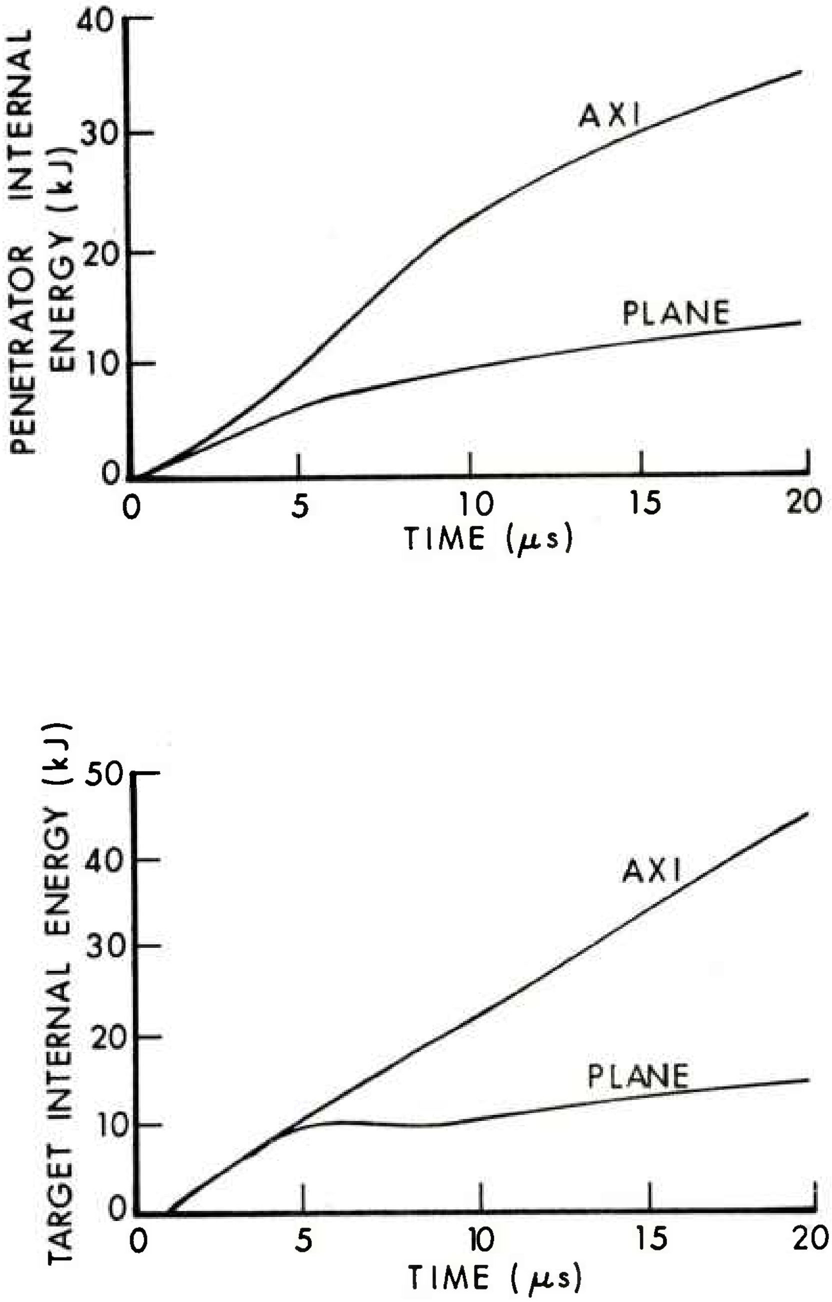


Figure A-13. Penetration and Target Internal Energy as a Function of Time for the Axisymmetric and Plane Strain Mode Calculations

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